

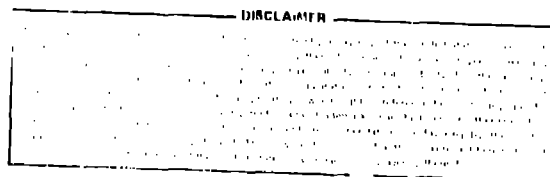
TITLE: AN OPTIMIZED DESIGN FOR PIGMI

MASTER

AUTHOR(S): L. Hansborough, R. Hamm, J. Stovall, D. Swenson

SUBMITTED TO: 6th Conference on the Application of Accelerators
in Research and Industry, Denton, TX, Nov. 3-5, 1980.

University of California



By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.



LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

An Affirmative Action/Equal Opportunity Employer

AN OPTIMIZED DESIGN FOR PIGMI*

L. Hansborough, R. Hamm, J. Stovall, and D. Swenson
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Summary

PIGMI (Pion Generator for Medical Irradiations) is a compact linear proton accelerator design, optimized for pion production and cancer treatment use in a hospital environment. Technology developed during a four-year PIGMI Prototype experimental program allows the design of smaller, less expensive, and more reliable proton linacs. A new type of low-energy accelerating structure, the radio-frequency quadrupole (RFQ) has been tested; it produces an exceptionally good-quality beam and allows the use of a simple 30-kV injector. Average axial electric-field gradients of over 9 MV/m have been demonstrated in a drift-tube linac (DTL) structure. Experimental work is underway to test the disk-and-washer (DAW) structure, another new type of accelerating structure for use in the high-energy coupled-cavity linac (CCL). Sufficient experimental and developmental progress has been made to closely define an actual PIGMI. It will consist of a 30-kV injector, an RFQ linac to a proton energy of 2.5 MeV, a DTL linac to 125 MeV, and a CCL linac to the final energy of 650 MeV. The total length of the accelerator is 133 meters. The RFQ and DTL will be driven by a single 440-MHz klystron; the CCL will be driven by six 1320-MHz klystrons. The peak beam current is 28 mA. The beam pulse length is 60 μ s at a 60-Hz repetition rate, resulting in a 100- μ A average beam current. The total cost of the accelerator is estimated to be ~\$10 million.

Introduction

Since its inception, cancer radiotherapy has become increasingly dependent upon particle accelerators for generating radiation. Negative pions for cancer radiotherapy possess many characteristics that

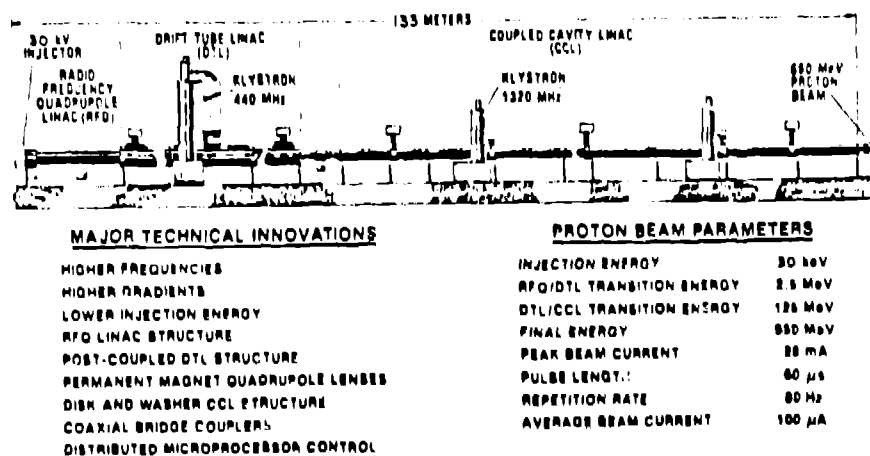
*Work performed under the auspices of the National Cancer Institute, Division of Research and Centers, U. S. Department of Health, Education and Welfare.

may make them superior to conventional radiations. Accelerators for producing the 600- to 800-MeV protons necessary to generate therapeutically useful beams of pions have been large and expensive. However, linear accelerators are attractive as medical pion generators for several reasons: they can accelerate large currents with very low beam loss, and generally exhibit high ac power to beam-power conversion efficiencies.

As part of the PIGMI program, detailed beam-dynamics studies have been done to assess innovative configurations that could result in major system simplification or cost reduction. Prototype fabrication and testing of subsystems have been an essential part of the effort. New technological concepts that have been evaluated include: (1) very low-energy injection systems, (2) permanent-magnet focusing systems, (3) high electric field-gradient operation, (4) the RFQ accelerator, (5) coupled-cavity DAW linac structure, (6) modulating-anode klystron systems for high-power operation, (7) bright-acid-leveling copper-plating of accelerator components, and (8) resonantly coupled accelerating structures to reduce the complexity and cost of the RF system. The result is shown schematically in Fig. 1, an optimized design of a 133-m-long PIGMI proton linear accelerator for producing therapeutic beams of pions.

Injector

The injector system has normally been an expensive and complicated component of any linac. The small PIGMI injector, utilizing a duoplasmatron ion source, operates at only 30 kV. The 30-keV injection energy is selected by the beam dynamics requirement in the RFQ for efficient bunching in a minimum distance, and is consistent with a single-gap high-brightness extraction system. The single-gap convergent extraction geometry extracts a 36-mA beam at 30 keV, and a simple, three element, unipotential einzel lens provides electrostatic focusing of the ion beam into the RFQ. The distance from the injector extraction aperture to the beginning of the RFQ linac



PROTON LINAC PARAMETERS

	FREQUENCY	KLYSTRONS	GRADIENT
RFQ & DTL SECTION	440 MHz	1	9 MV/m
CCL SECTION	1320 MHz	6	9 MV/m

Fig. 1. Pion Generator for Medical Irradiation (PIGMI)

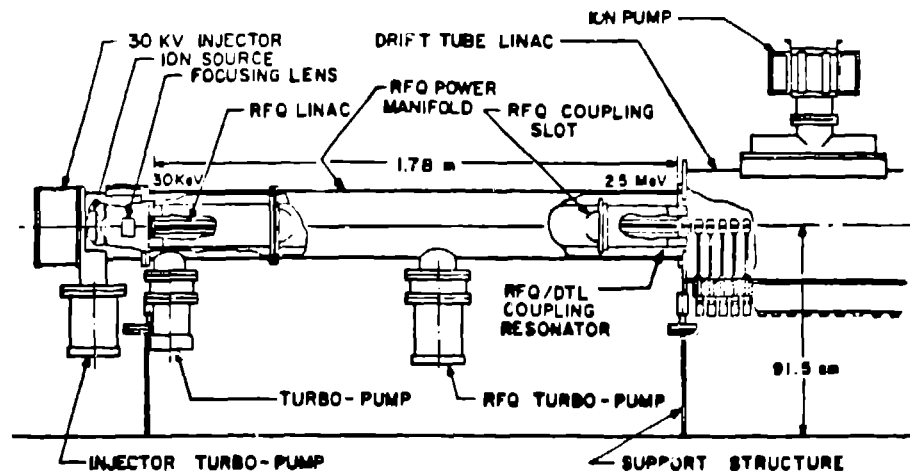


Fig. 2. PIGMI injector and RFQ linac.

is only 15 cm. The injector power supply is shielded within a standard control rack with voltage protection provided by inexpensive lucite covers.

Radio-Frequency Quadrupole Linac

The 440-MHz RFQ linac dramatically simplifies the front end of the accelerator shown in Fig. 2. The RFQ is a remarkably simple accelerating structure, and, once tuned, requires no further adjustments. The first RFQ structure in the western world was tested in the PIGMI laboratory in February, 1980. The tests were highly successful;² the principles of an RFQ linac are described in Ref. 3. The PIGMI RFQ linac is 1.78 m long; it focuses, bunches and accelerates the proton beam from the injection energy of 30 keV to a final energy of 2.5 MeV. Power is coupled into the RFQ from the DTL. The PIGMI RFQ's average accelerating gradient is about 1.4 MeV/m.

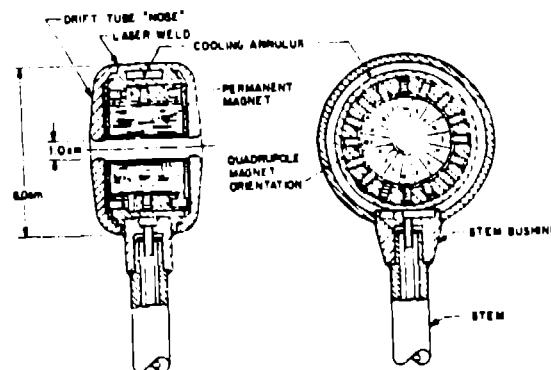


Fig. 3. DTL drift-tube design.

Drift-Tube Linac

The PIGMI DTL is a refinement of the post-coupled Alvarez structure drift-tube linac. Only one klystron is required, feeding the DTL structure through a single iris. The 440-MHz DTL is a single-cavity, post-coupled structure ~30 m long that accelerates the beam from 2.5 MeV to 125 MeV. It contains 150 drift tubes. The DTL structure is very reliable and requires a minimum of control, once properly tuned. An RF power gradient test cavity (PIGLET) has been tested in the PIGMI laboratory to an average axial electric field gradient of greater than 9 MV/m; however, a more conservative average axial electric field gradient of 6 MV/m has been chosen to PIGMI.

The drift tubes are copper plated stainless steel, each of which contains an identical, small permanent-magnet quadrupole lens to focus the beam. The length of the drift tube varies from a minimum of ~4 cm to a maximum of ~24 cm. The drift tube and quadrupole geometry are shown in Fig. 3.

The DTL is fabricated in twelve tank sections, each about 2.5 m in length, that utilize the saddle approach developed for the PIGMI Prototype. Table I describes the characteristics of each tank section. Each tank section is stiffened along the bottom by a structural member which is used to support and align the drift tubes. Two slots in the top of the tank section allow access to the interior and the installation of vacuum pumps, fixed tuners, variable tuners, etc. The tank sections are fabricated from mild steel with a copper plated interior. Each tank section is assembled, tuned, aligned, leak checked, and sealed at the factory prior to installation at

Table I
PIGMI Drift Tube Linac Tank Sections

Tank Section	Length (M)	Number of Drift Tubes	Final Energy (MeV)
1	2.502	30	13.4
2	2.570	19	25.0
3	2.375	14	35.7
4	2.556	13	47.2
5	2.411	11	57.5
6	2.624	11	68.5
7	2.557	11	78.7
8	2.433	9	88.2
9	2.550	9	97.8
10	2.360	8	106.5
11	2.443	8	115.2
12	2.680	8	125.0
Total	30.061	150	125.0

the site--a rather simple assembly operation with only minor tuning required.

Transition Region

The short (1.9-m-long) transition region between the DTL and CCL is shown in Fig. 4. This region separates the 440-MHz portions of PIGMI from the 1320-MHz portion, and it provides a place to examine and adjust beam conditions prior to further acceleration in the CCL. The transition region contains the only electromagnets (except for those necessary in the injector) in the entire PIGMI accelerator; all other magnets are permanent magnets.

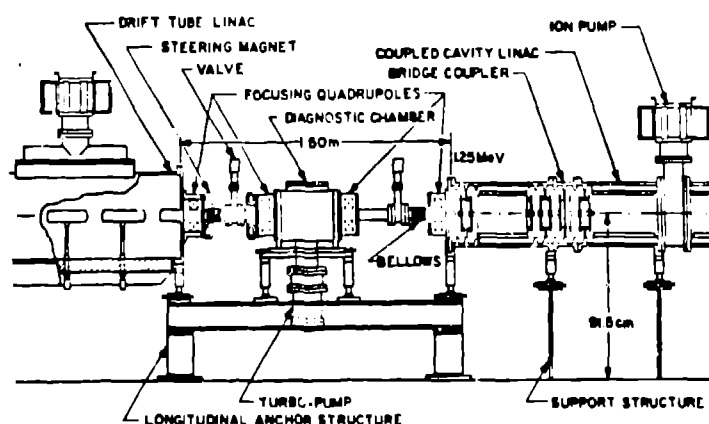


Fig. 4. Transition region between the DTL and CCL.

Coupled-Cavity Linac

The CCL is the longest part of the PIGMI accelerator. It is a 1320-MHz structure that accelerates the beam from 125 MeV to 650 MeV in ~99 m, with an average axial electric field gradient of 8 MV/m. The PIGMI CCL is comprised of 108 tanks, with lengths varying from 0.6 m to 1.0 m. Each tank contains 11 cells; the cell geometries are uniform throughout each tank, but differ from tank to tank. The tanks are resonantly coupled by 107 single-cell bridge couplers, each containing an identical permanent-magnet quadrupole singlet for focusing the beam. A view of the disk-and-washer structure is shown in Fig. 5. A single-cell bridge coupler for the PIGMI

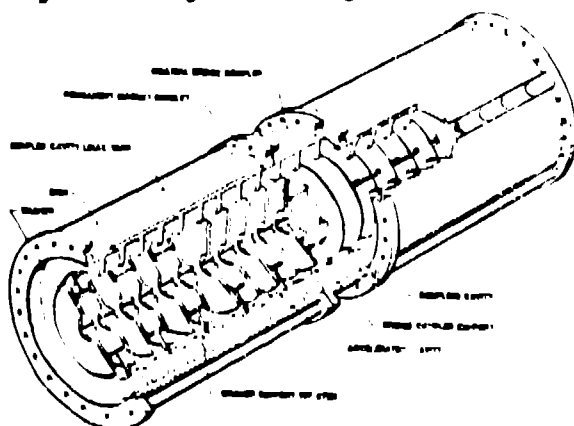


Fig. 5. CCL accelerating tank and bridge coupler.

application is adequate to house the required auxiliary apparatus (beam-focusing quadrupoles and beam-diagnostic equipment) within the linac structure. Because the cell-to-cell coupling coefficients are so large, the entire CCL operates as one resonant unit. This allows operation with a minimum amount of control, once the initial tuning operation has been done.

For the purpose of facility organization, the CCL is subdivided into 6 modules. Each module is powered by a 1320-MHz klystron. A high degree of similarity exists between modules with regard to the distribution of the necessary auxiliary features such as RF drive points, diagnostic instrumentation, and vacuum equipment. Each module consists of 18 accelerating tanks and 18 coaxial bridge couplers that separate the accelerating tanks. The length and maximum energy associated with each module are given in Table II. A typical module is shown in Fig. 6.

Table II
PIGMI Coupled-Cavity Linac Modules

Modules	Length (m)	Number of Tanks	Final Energy (MeV)
A	12.60	18	193
B	14.61	18	271
C	16.22	18	357
D	17.52	18	450
E	19.58	18	548
F	19.42	18	650
Total 6	99.93	108	650

During the assembly of each tank, the parts are temporarily installed and tuned. If required, changes may be made to the individual washers, and fabrication of the tank is completed. The tanks are then joined together in small groups to test the properties of the bridge couplers; minor changes required in the bridge couplers can be made at this time. Finally, the entire CCL structure is assembled at its final destination with only minor final tuning required.

RF Power System

The PIGMI frequencies of 440 MHz and 1320 MHz were chosen partly on the basis of beam dynamics considerations and partly on the availability of suitable klystrons. The 60-μs, 60-Hz beam duty factor was adopted for PIGMI on the basis that the power savings resulting from the lower repetition rate overrides the additional cost of the pulse-forming network (PFN) modulators associated with the long pulse length. The total peak power 440-MHz requirement is 19.7 MW; the average power requirement is 89.4 kW; these can be satisfied by one Varian VA-812E klystron.

The cavity peak-power requirement for the 1320-MHz portions of PIGMI is 81.4 MW and the average-power requirement is 310.6 kW. Five Litton L-5081 klystrons are capable of satisfying both the peak-and-average-power requirements of the 1320 MHz portion of PIGMI; however, the PIGMI design is based on six such klystrons operating at a reduced level, providing the possibility of continued operation in the event of the outage of a single klystron.

Control and Instrumentation System

A PIGMI accelerator is designed so that once turned on and tuned up, it can run reliably unattended. Therefore, the major role of the accelerator control system is a passive one its primary tasks are to monitor all facets of routine machine operation, to detect faults, and to alert the operator to abnormal, or impending abnormal, situations. When necessary, corrective action can be automatic. Data can be collected automatically on a regular basis, and the system will support accelerator maintenance by effective diagnostic testing. It provides straightforward and, in some cases, automatic procedures for machine turn-on, tune-up, and fault recovery.

The design is based on a collection of small, modular, intelligent control stations, each of which is associated with an accelerator module, or a logical collection of equipment, requiring control and associated signal sources. This approach produces an extremely flexible and reliable control system. Each control station would include a single-board computer, a small equipment-oriented console, and the analog

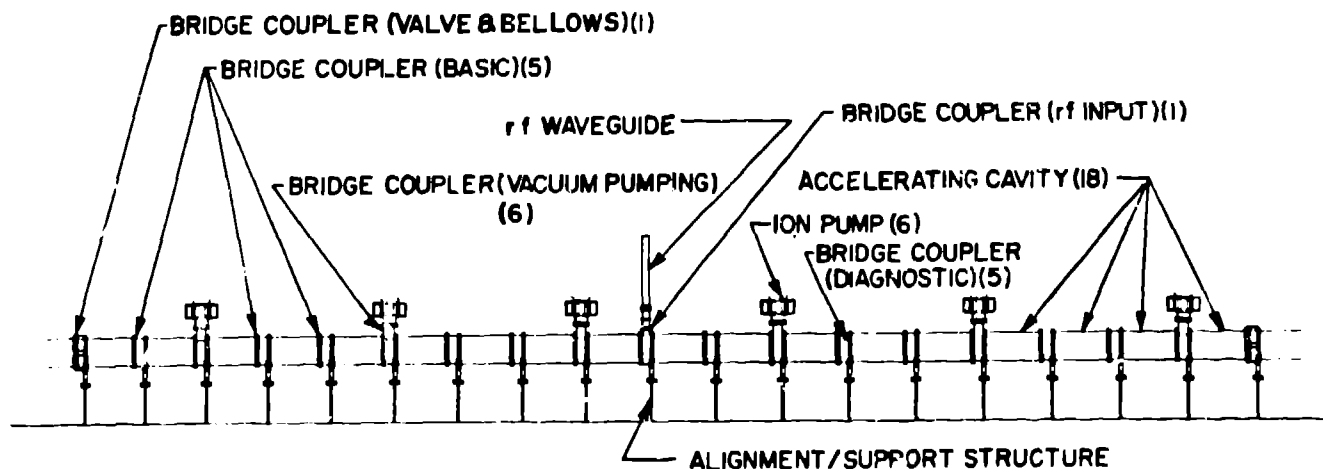


Fig. 6. Typical CCL Module.

and digital interface equipment. All of these components are compatible with the MULTIBUS, an industry standard microcomputer bus specification that is currently supported by over 50 manufacturers of compatible equipment.

The primary interface between the operator and the accelerator would be at a modest control console. Display equipment would include a color CRT for status displays, interactive control and limited graphics, and a storage scope for general-purpose graphics. Knobs under operator control would facilitate most manual tuning operations. Operators and engineers would have a variety of software tools at their disposal, many of which could be executed concurrently. However, it is entirely possible that normal accelerator operation can be accomplished by the positioning of a switch to the appropriate position: OFF, STANDBY or ON.

Conclusion

It was recognized from the beginning that PIGMI, as a medical device, represents a different breed of proton accelerator from the much more familiar research accelerators. A very attractive feature of the PIGMI accelerator is its stark simplicity. There are only two resonant units, one at 440 MHz, and one at 1320 MHz. Almost all magnetic quadrupoles are permanent-magnet type, which require no power supplies or associated instrumentation. The injection voltage is supplied by a rack-mounted 30-kV power supply. In all, there are very few power supplies and very few active control parameters, all of which are handled by a modest, distributed, MULTIBUS-based control system. The optimized design of PIGMI provides a linear accelerator tailored to the needs of the medical community; that is, it is relatively inexpensive, compact, reliable, provides the required beam intensity and energy, and is economical to operate.

A complete PIGMI facility will require a construction time of ~2 years, from the beginning of site preparation to the beginning of patient treatment. Two-shift (16 hours per day) operation is possible with a staff of 8 people. A cost estimate has been made, based on the present level of the PIGMI design. The construction cost of only the accelerator is estimated to be approximately \$10 million in 1980 dollars. Not included in this cost estimate are service building/office space, cooling costs, accelerator tunnel costs, and contingency funds. These will be dictated by the needs or location of the medical center at which the PIGMI facility will be installed.

Acknowledgments

The development of the PIGMI design is the product of the contribution of approximately 60 individuals. The authors would particularly like to acknowledge the contributions of R. H. Stokes, T. P. Wangler, K. R. Crandall, J. M. Potter, and S. O. Schriber in the areas of beam dynamics and accelerator structures, T. J. Boyd and P. J. Tallerico in the area of RF power, S. F. Klosterbuer in the area of accelerator control system development, and the contributions of the mechanical and electronic technicians (R. F. DePula, F. J. Humphrey, J. L. Johnson, D. R. Keffler, T. A. Lopez, and V. A. Martinez) who helped develop and implement the PIGMI prototype equipment.

References

1. L. D. Hansborough (Ed.), "PIGMI: A Design Report for a Pion Generator for Medical Irradiations," LASL report (in preparation).
2. J. E. Stovall, K. R. Crandall, R. W. Hamm, "Performance Characteristics of a 425-MHz RFQ Linac," these proceedings.
3. T. P. Wangler and R. H. Stokes, "The Radio-Frequency Quadrupole Linear Accelerator," paper, these proceedings.